MODELLING OF CLOUDLESS SOLAR RADIATION FOR PV MODULE PERFORMANCE ANALYSIS

Deo Dusabe — Josiah Munda — Adisa Jimoh *

The empirical model developed in this study uses standard specifications together with actual solar radiation and cell temperature to predict voltage-current characteristics of a photovoltaic panel under varying weather conditions. The paper focuses on the modelling of hourly cloudless solar radiation to provide the insolation on a PV module of any orientation, located at any site. The model is built in Matlab/Simulink environment to provide a tool that may be loaded in the library. It is found that the predicted solar radiation strongly agrees with the experimental data from the National Renewable Energy Laboratory (NREL). Further, a satisfactory agreement between the predicted voltage — current curves and laboratory measurements is obtained.

K e y w o r d s: solar energy, solar radiation, solar cells, photovoltaic module, modelling and simulation

1 INTRODUCTION

The design and analysis of photovoltaic modules require a tool that can predict the behaviour of photovoltaic generators under various weather conditions. Manufacturers usually provide electrical specifications of the PV panels at standard conditions, namely solar radiation of $1000\,\mathrm{W/m^2}$ and cell temperature of $25\,^\circ\mathrm{C}$.

To characterize the performance of a photovoltaic (PV) module under varying weather conditions, simulation models of PV modules have been developed [1, 2]. One of the required inputs for these models is the solar radiation impinging the panel. However, solar data are not always available at all sites. Where they are available, solar data are limited to historical records of global irradiance, also called insolation on a horizontal surface, which are taken at meteorological stations. Therefore there is a need for models that can provide solar radiation information on a plane surface of any orientation.

Several models have been reported [3–5]. Building on these models, with additional tests on the zenith angle, this paper develops a Matlab/Simulink block to generate solar radiation at any location and for any time of the year. Thereafter the obtained solar data are fed to the photovoltaic module model given in [1], thereby yielding an extended PV module model to investigate the performance of a photovoltaic flat — panel of any orientation. The contribution of the paper is that the extended PV module model developed in this study has the advantage of exclusively using the specifications provided in the manufacturer's data sheet. The model developed in [2] requires the difficult task of evaluating the ideal factor of the diode to adjust the curve fitting parameter.

2 MODEL DESCRIPTION

Hourly cloudless solar radiation

The general form of the model is given as follows [3]

$$G_{TP} = G_{BP} + G_{DP} + G_{RP} \tag{1}$$

where G_{TP} is the total radiation on a tilted flat — panel, G_{BP} is the direct solar beam on the panel, G_{DP} is the diffuse radiation on the panel, and G_{RP} is the ground reflected irradiance on the tilted panel.

Direct solar beam radiation

The expression of the direct beam radiation is given as follows [5]

$$G_{BP} = G_B \cos\theta \tag{2}$$

where G_B is the direct beam radiation at the surface of the earth and θ is the angle of incidence between the normal to the panel face and the incoming direct beam.

It has been reported that in the presence of a homogeneous atmosphere of finite depth H, containing absorbing and scattering agents such as dust, air pollution, atmospheric water vapour, and clouds, the attenuation of the intensity of the direct radiation on a surface normal to the beam follows the Beer's law [4], given by

$$\frac{\mathrm{d}g_b}{\mathrm{d}l} = -f g_b \tag{3}$$

where g_b is the intensity of the beam radiation, f is the concentration of intercepting agents, and l is the distance traveled.

After analytic manipulations of (3), the expression for beam radiation at the surface becomes

$$G_B = G_0 \exp\Big(-\frac{fh}{\sin\beta}\Big) \tag{4}$$

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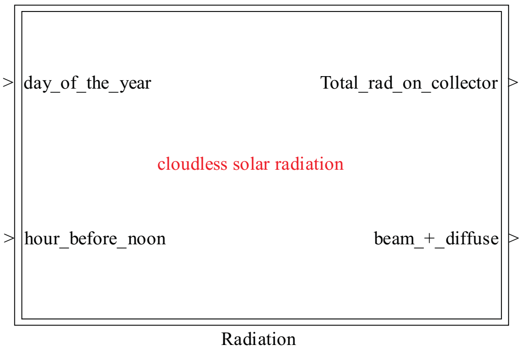

Fig. 1. Matlab/Simulink structure for solar radiation

where G_0 is the extraterrestrial radiation, h is the distance between the ground and the top of the atmosphere, and β is the altitude (zenith) angle of the sun, which is the angle between the sun and the local horizontal beneath the sun.

A similar expression is provided in [3], where the factor $f * h$ called the optical depth is noted as k along with equations to compute the extraterrestrial flux (5) and the optical depth (6)

$$G_0 = 1160 + \sin\frac{360(n-275)}{365}\,, \tag{5}$$

$$K = 0.174 + 0.035\sin\frac{360(n-100)}{365} \tag{6}$$

where n is the day number with January 1 as 1 and December 31 is the day number 365.

Similarly, expressions are available for calculating the incident angle and the altitude angle [3]

$$\cos\theta = \cos\beta\cos(\phi_S - \phi_P)\sin\varphi + \sin\beta\cos\varphi\,, \tag{7}$$

$$\sin\beta = \cos L\cos\delta\cos H + \sin L\sin\delta \tag{8}$$

where φ is the slope of the panel, ϕ_P is the azimuth angle of the panel, which is measured relative to south, with positive values in the southeast direction and negative values in the southwest. In the southern hemisphere, ϕ_P takes the opposite sign.

The azimuth angle of the sun ϕ_S is given by

$$\phi_S = \sin^{-1}\frac{\cos\delta\sin H}{\cos\beta} \tag{9}$$

where the declination δ, which is the angle between the plane of the equator and a line drawn from the centre of the earth, is given by [6].

$$delta = 23.45\sin\frac{360(284+n)}{365.25} \tag{10}$$

and the hour angle H is given by

$$H = \frac{15^\circ}{hour}(hours\_before\_solar\_noon)\,. \tag{11}$$

In the equations given above, n is the day number, and the "hours before solar noon" is positive before noon and negative after noon. For example, the angle hour is equal to $+15^\circ$ at 11:00 am and -15° at 1:00 pm.

The following test must be done to determine whether the azimuth angle of the sun is greater or less than 90° away from the south

$$\text{If } \cos H \ge \frac{\tan\delta}{\tan L},\ \text{then } abs(\phi_S) \le 90^\circ\,; \quad \text{otherwise } abs(\phi_S) > 90^\circ\,. \tag{12}$$

The term $1/\sin\beta$ in equation (4), is called the air mass, which is the ratio of the air mass that the direct radiation would traverse at any given time and location to the air mass that the direct radiation would traverse when covering its shortest distance. It is important to point out that the altitude angle β is always positive. This paper provides the following test to meet this constraint

$$\text{If } \beta > 0,\ \text{then } G_B = G_0\exp\Big(-\frac{k}{\sin\beta}\Big)\,; \quad \text{otherwise } G_B = 0\,. \tag{13}$$

Matlab/Simulink Implementation

The obtained equations (5)–(12) are put in equation (13), then in (2) to compute the direct beam radiation on a flat — panel. Figure 9 shows the Matlab/Simulink structure to calculate this radiation component.

Diffuse radiation and reflected radiation

The analytic expression of the diffuse radiation developed in [4] requires the knowledge of the scattering ratio, the zenith transmittance, and the albedo factor. The models used in this study are reported in [3].

Diffuse radiation

The model of diffuse component of radiation on a flat — panel is given by

$$G_{DP} = SG_B\Big(\frac{1+\cos\varphi}{2}\Big) \tag{14}$$

where the sky diffuse factor S is computed as follows

$$S = 0.095 + 0.04\sin\frac{360(n-100)}{365} \tag{15}$$

with G_B, φ, and n are variables defined above.

Reflected radiation

The reflected radiation term on a surface of any direction is modelled as follows

$$G_{RP} = \rho G_B(\sin\beta + S)\frac{1-cos\varphi}{2} \tag{16}$$

where ρ is the ground reactance also called albedo.

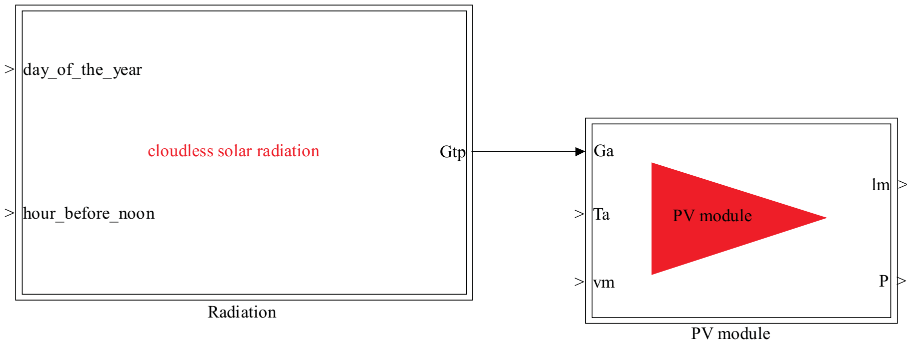

Fig. 2. Matlab/Simulink structure for PV module

Total solar radiation on a flat photovoltaic module

Equations (2), (14), and (16) are summed up to compute the total solar radiation as follows

$$G_{TP} = G_0 \exp\Big(-\frac{k}{\sin\beta}\Big)\Big[\cos\beta\cos(\phi_S-\phi_C)\sin\varphi + + S\Big(\frac{1+\cos\varphi}{2}\Big) + \rho(\sin\beta+S)\frac{1-\cos\varphi}{2}\Big]. \qquad (17)$$

Figure 1 shows the masked representation of equation (17) in Matlab/Simulink.

Photovoltaic module

The PV module model used in this paper is reported in [1]. The expression of the current is given by

$$I_{sm} = I_{scm}\Big[1 - \exp\frac{V_{sm}-V_{ocm}+R_{sm}I_{sm}}{\alpha_t}\Big] \qquad (18)$$

where

$$\alpha_t = \alpha_{t,0}\frac{T_j+273}{T_{j,0}+273} \qquad (19)$$

is the thermal voltage timing completion factor at operation point. The thermal voltage timing completion factor at standard conditions is given by

$$\alpha_{t,0} = \frac{2V_{mp,0}-V_{ocm,0}}{\frac{I_{scm,0}}{I_{scm,0}-I_{mp,0}} + \ln\big(1-\frac{I_{mp,0}}{I_{scm,0}}\big)}\,. \qquad (20)$$

The rated voltage $V_{mp,0}$, open circuit voltage $V_{ocm,0}$, rated current $I_{mp,0}$ Imp,0, and short circuit current $I_{scm,0}$ at standard condition are known from the manufacturer's data sheet. $T_{j,0} = 25\,°\mathrm{C}$, and $G_{TP,0} = 1000\,\mathrm{W/m^2}$ define the cell temperature, and total solar radiation on the panel at standard conditions respectively. T_j is the cell temperature.

The parameters in equation (18) are computed as follows.

- Short circuit current

$$I_{scm} = I_{scm,0}\frac{G_{TP}}{G_{TP,0}}\Big(1+\frac{E(T_j-T_{j,0})}{I_{scm,0}}\Big) \qquad (21)$$

- Open circuit voltage

$$V_{ocm} = V_{ocm,0}\Big(1+\frac{C(T_j-T_{j,0})}{V_{ocm,0}}\Big) \times \log\big(2.72 + D(G_{TP}-G_{TP,0})\big) \qquad (22)$$

- Series resistance

$$R_{sm} = \frac{\alpha_{t,0}\log\big(1-\frac{I_{mp,0}}{I_{scm,0}}\big) - V_{mp,0} + V_{ocm,0}}{I_{mp,0}}\,. \qquad (23)$$

In the above expressions, G_{TP} is given by equation (17). The temperature coefficient of short circuit current E and the temperature coefficient of open circuit voltage C are found in electrical specifications of the module. The constant $D = 0.005\,\mathrm{m^2/W}$.

Thermal model

The cell or junction temperature is related to the ambient temperature as follows

$$T_j = T_a + A + BG_{TP} \qquad (24)$$

where $A = -2.89\,°\mathrm{C}$ and $B = 0.034\,°\mathrm{Cm^2/W}$ are constants.

Figure 2 depicts the implementation of equation (18) in Matlab/Simulink environment where the solar radiation is computed using Fig. 1.

3 VALIDATION AND DISCUSSIONS

Hourly cloudless solar radiation

To validate the solar radiation model (17), Fig. 1 was run in Matlab/Simulink environment. The simulated results were compared with the data from National Renewable Energy Laboratory (NREL) as recorded in [3]. Table 1 contains the predicted and the measured values while Fig. 3 depicts the predicted (solid lines) results and the measurement data (asterisks).

From Fig. 3, the excellent agreement between the simulated results and the measured values is obvious. The absolute percentage error varies from 0 to 0.17 %. Therefore

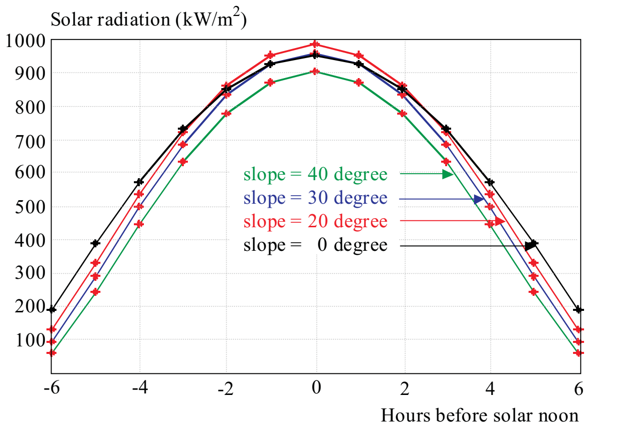

Fig. 3. Hourly clear-sky solar radiation (beam + diffuse), latitude = 40N, solid lines = simulations results, asterisks = measured data

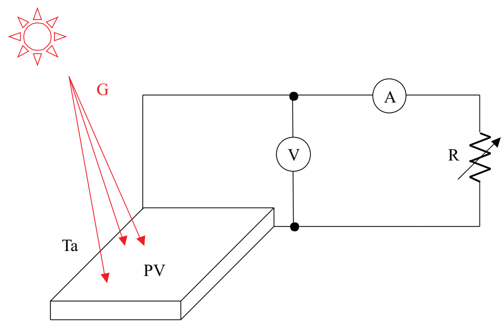

Fig. 4. Experiment set up

the clear solar radiation model and its Simulink representation can be used to satisfactorily predict the hourly solar radiation on a flat PV panel at any location and any orientation. Having determined the irradiance on the PV module of any orientation, which is one of the inputs of the PV module model, the next section deals with the validation of the photovoltaic module model as presented in section 2.

Experimental Set-up

A set of measurements recorded from experiment done on the PV panel Shell PowerMax Ultra 75 — P [7] on May 9th and May 12th, 2008, is used to validate the modelling of the PV module. Figure 4, which consists of a photovoltaic panel, voltmeter, ampere meter, and rheostat, shows the diagram used to record a series of readings of voltage and current. The ambient temperature in the vicinity of the panel was measured using the digital heat regulator HT NIPt—IP7A.

The data sheet of the used panel is given in the appendix. However, some of the specifications at standard conditions recorded in data sheets were different from the data provided with the PV module. The following values were used for simulation purpose.

Maximum power $P_{\max,0} = 75$ W, Rated voltage $V_{mp,0} = 17.3$ V, Rated current $I_{mp,0} = 4.3$ A, Open circuit voltage $V_{ocm,0} = 21.7$ V, and Short circuit current $I_{scm,0} = 4.8$ A.

The panel was exposed to solar radiation, and the sun intensity was calculated using the model developed in section 2.1.

Results

Figure 5 and 6 show the simulated results (solid lines) and the experimental data (asterisks) on May 9th at 12:00 am and on May 12th 2008 at 10:00 am, where the sky was clear. The differences between the recorded and the predicted values are mainly due to uncertainties inherent in the experimental data namely error in readings, calibration error, and so on. To investigate the effect of eventual experimental errors, 1V was subtracted from the measurements of high voltages recorded on the 9th May, 2008 (Fig. 7).

As can be seen, Fig. 7 shows a very good agreement between the (voltage, current) points determined by the model and monitored data. The accuracy of the results could be improved if high precision apparatus were used and readings taken simultaneously by three different persons. In addition, the use of a pyranometer would reduce

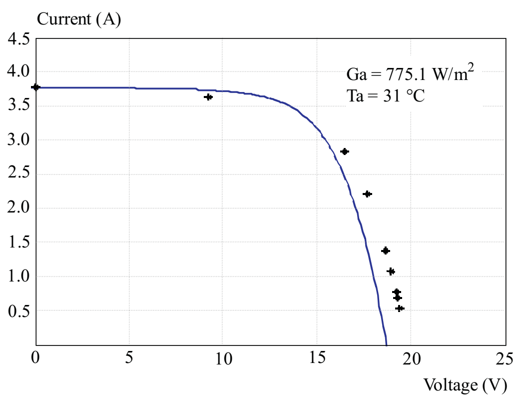

Fig. 5. Experimental and predicted data of (V, I) for PV module; day = 129 (09/05) at noon; slope = 5 degree

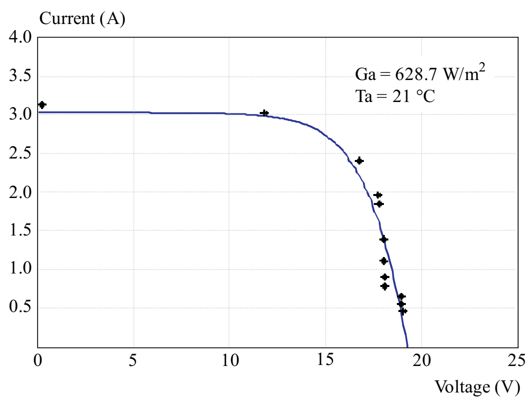

Fig. 6. Experimental and predicted data of (V, I) for PV module; day = 132 (12/05) at 10:00 am; slope = 5 degree

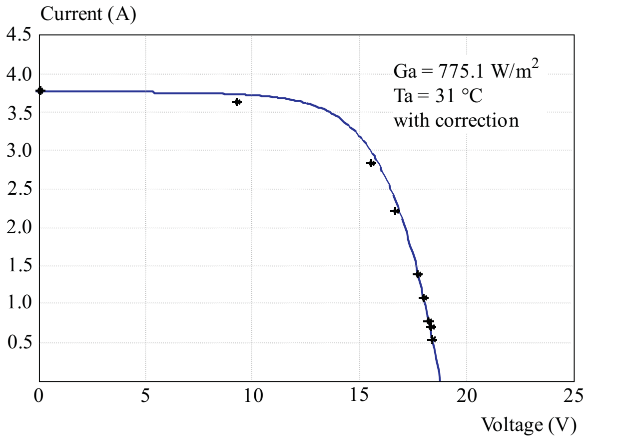

Fig. 7. Experimental and predicted data of (V, I) for PV module; day = 129 (09/05) at noon; slope = 5 degree

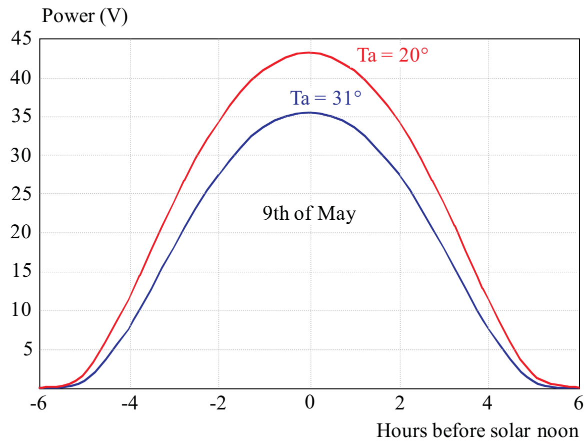

Fig. 8. Output power

the eventual errors introduced when computing solar radiation values.

Output power

The validated model developed above and its Simulink structure (Fig. 2) can be used to predict the output power of a panel of any orientation at any clear sky location. In this paper, Fig. 2 is used to predict the output power of the 75 — P panel on the 9th May, 2008 at Pretoria, South Africa (Latitude = 25.8S).

Figure 8 shows the output power when the daily average is 31 °C and 20 °C respectively.

As can be seen, the output power is zero when the solar radiation is low from 5:00pm up to 7:00am. The output power reaches its maximum at noon since at this time; the intensity of solar insolation is at its highest value. This perfectly agrees with the power property of the PV module, which states that the output power of the panel is directly proportional to the solar radiation impinging the PV module [8].

Figure 8 also greatly demonstrates the dependency of output power on the ambient temperature. It is known that the output power of the panel is inversely proportional to the ambient temperature [3], [8], [9]. From Fig. 8, it is obvious that the output power at 20 °C is greater than the corresponding output power at 31 °C. This good agreement between properties from literature and predicted results suggests that the models and their Simulink structures can be satisfactorily used to predict the performance of the PV module of any orientation at any cloudless location.

4 CONCLUSION

This paper has provided a tool to predict the performance of a PV module of any orientation, at any cloudless location using Matlab/Simulink environment. The cloudless hourly solar radiation presented in this study uses simple, empirical equations to predict solar radiation striking the solar flat — panel. The predicted results greatly agree with the experimental data provided by the National Renewable Energy Laboratory. The empirical PV module model has shown good accuracy when compared with experimental results. However, this accuracy would be improved if errors inherent in experimental work were reduced.

Future work will deal with improving the model by including additional parameters such as shunt resistance and material band gap. Another area will be the upgrade of the solar radiation model by taking into account factors such as cloud, dust, and aerosol dispersion.

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APPENDIX

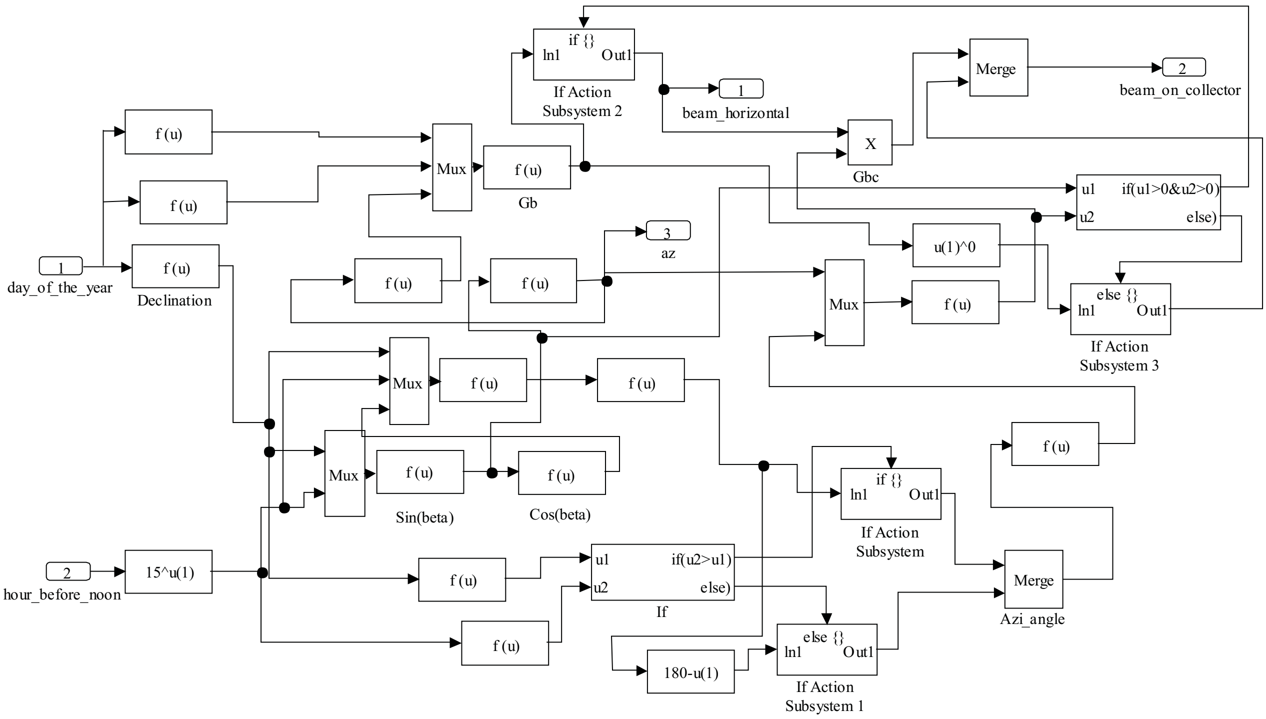

Fig. 9. Matlab/Simulink structure of the beam radiation

Data at Standard Test Condition (STC)

STC: irradiance level 1000 W/m^2, spectrum AM 1.5 and cell temperature 25 °C.

	Shell PowerMax	Ultra 75-P	Ultra 70-P
Rated power (W)	P_r	75	70
Peak power* (W)	P_{mpp}*	75	70
Module efficiency (%)	η	11.9	11.1
Maximum system voltage	V_{sys}	600	600
Peak power voltage (V)	V_{mpp}	16.6	16.3
Peak power current (A)	I_{mpp}	4.54	4.32
Open circuit voltage (V)	V_{oc}	21.4	21
Short circuit current (A)	I_{sc}	5.25	5.15
Series fuse rating (A)	I_{fuse}	20	20
Peak peak power (W)	$P_{mpp\,\mathrm{min}}$	71.25	66.5
*Tolerance in peak power (%)		±5	±5

*The abberevation ‘mpp’ stand for Maximum Power Point

Typical data at nominal operating cell temperature (NOCT) conditions

NOCT: Irradiance level 800 W/m^2, spectrum AM 1.5, wind velocity 1 m/s, T_{noct} 20 °C.

Temperature (°C)	T_{NOCT}	45.5	45.5
Peak power (W)	P_{mpp}	55	51
Peak power voltage (V)	V_{mpp}	15.2	14.6
Open circuit voltage (V)	V_{oc}	19.9	19.8
Short circuit current (A)	I_{sc}	4.15	4.10
Temperature coefficient			
P_{mpp} (%/ °C)		−0.43	−0.43
V_{mpp} (mV/ °C)		−72.5	−72.5
I_{sc} (mA/ °C		1.4	1.4
V_{oc} (mV/ °C)		−64.5	−64.5

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